



Energy efficiency of winter wheat in a long-term tillage experiment under Pannonian climate conditions



Gerhard Moitzi^{a,*}, Reinhard W. Neugschwandtner^b, Hans-Peter Kaul^b, Helmut Wagentristl^a

^a University of Natural Resources and Life Sciences, Vienna (BOKU), Department of Crop Sciences, Experimental Farm Groß-Enzersdorf, Schloßhofer Straße 31, 2301 Groß-Enzersdorf, Austria

^b University of Natural Resources and Life Sciences, Vienna (BOKU), Department of Crop Sciences, Division of Agronomy, Konrad-Lorenz-Straße 24, 3430 Tulln an der Donau, Austria

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ABSTRACT

One goal in sustainable agriculture is to use fossil energy more efficiently in crop production. Information on energy consumption and efficiency of different soil tillage systems for developing energy-efficient farming systems with reduced impact on climate change is missing for the Pannonian Basin. This 12-year study on a silt loam chernozem investigated the energy efficiency of four tillage systems (mouldboard plough (MP), deep conservation tillage (CT_d), shallow conservation tillage (CT_s), no-tillage (NT)) in rotations taking thereby into account diesel fuel consumption, total energy input (made up of both direct and indirect inputs), grain yield, energy output, net-energy output, energy intensity and energy output/input-ratio. Input rates of fertilizer, herbicides and seeds remained constant, while values of diesel fuel consumption were measured for all tillage operations. Total diesel fuel consumption for winter wheat (*Triticum aestivum* L.) production was 59.8 L ha⁻¹, 60.6 L ha⁻¹, 48.5 ha⁻¹ and 36.0 L ha⁻¹ for MP, CT_d, CT_s and NT, respectively. Between 73% and 83% of total energy input was required by indirect energy (seeds, fertilizer, herbicides, machinery). MP and CT_d each required a total energy input of about 9.3 GJ ha⁻¹; the total energy input for CT_s and NT was lower by 4.8% for both. Direct energy input (diesel and lubricant oil) was much lower with no-tillage (with 1.5 GJ ha⁻¹) than with mouldboard plough (with 2.4 GJ ha⁻¹), deep conservation tillage (with 2.5 GJ ha⁻¹) and shallow conservation tillage (with 2.0 GJ ha⁻¹). Grain yield and thus energy output were mainly influenced by year. The year effect on yield and energy efficiency parameters was larger than the tillage effect. Especially in dry years, ploughless tillage systems tended to respond with competitive yields. This resulted in an increase of energy efficiency parameters. Over all twelve years, winter wheat produced in the CT_s tillage system reached the highest net-energy and output/input-ratio with the lowest energy intensity.

1. Introduction

Soil tillage systems can be classified based on tillage intensity and soil cover with plant residues into conventional and conservation tillage systems (Loibl, 2006). Soil tillage influences soil chemical characteristics and nutrient distribution (e.g. of phosphorus and potassium) in the soil (Pekrun et al., 2003; Neugschwandtner et al., 2014) and soil physical characteristics like bulk density, pore volume and pore size distribution, infiltration, soil water supply, aggregate stability and penetration resistance (Liebhard, 1994; Liebhard et al., 1994; Liebhard, 1995). There are several benefits of ploughless conservation tillage systems in production: the deposition of organic residues on the surface reduces run-off and nutrient losses and promotes infiltration through macro-pores made by earthworms. In addition, the bearing capacity of

the topsoil and the subsoil can be improved, which reduces the risk of soil compaction by applying conservation tillage (Rosner et al., 2004; Brunotte and Sommer, 2009). Further, reduced soil tillage increases earthworm populations and plant colonisation by arbuscular mycorrhizal fungi and reduces disease incidence of wheat under moist cool conditions (Anken et al., 2004); they also found an increased pre-consolidation stress and better trafficability in the no-tillage system, whereas bulk density did not differ from other tillage systems. Thaler et al. (2012) show higher soil water storage capacity in conservation tillage systems in the semi-arid regions of Austria than those in soil inversion systems.

In arable farming, soil tillage is one of the greatest energy and labor consumers (Tabatabaefar et al., 2009; Moitzi et al., 2014; Szalay et al., 2015). Energy is used directly as fuel or electricity to operate machinery

* Corresponding author.

E-mail address: gerhard.moitzi@boku.ac.at (G. Moitzi).

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and equipment and indirectly for production of fertilizers, pesticides, machinery and seeds (Pelizzi et al., 1988). Arable farming has become increasingly mechanized, requiring significant energy inputs at particular stages of the production cycle to achieve optimum yields. In conventional tillage systems with ploughing, more than 50% of total fuel consumption is usually required for soil preparation and seeding alone (Moitzi et al., 2015). Total fuel consumption during soil tillage is mainly influenced by soil texture and soil type. Higher soil organic matter content (e.g. after manure fertilization) reduces fuel consumption of ploughing (McLaughlin et al., 2002). Depending on soil texture, fuel consumption increases by 0.5 L ha^{-1} (sand) to 1.5 L ha^{-1} (clay) per centimetre of ploughing depth (Kalk and Hülsbergen, 1999; Filipović et al., 2004; Moitzi et al., 2006). Shifting of tillage systems from ploughing to non-inversion tillage reduces direct energy input and working time (Dutzi, 2008; Brunotte and Sommer, 2009). These economic benefits are the main reasons why conservation tillage systems are practised increasingly in many regions worldwide. Analysis of tillage systems in Sweden showed that overall energy use in tillage as a proportion of total energy used for crop production ranged from 5% for direct drilling on a silt loam soil to 25% for mouldboard ploughing on clayey soil (Arvidsson, 2010).

Agricultural practices and particularly soil tillage have a significant impact on increases in atmospheric CO_2 and greenhouse gases which have occurred in the last few decades (Lal, 1997; Tilmann et al., 2002). These CO_2 -emissions are caused by energy input, i.e. direct input through fossil fuel consumption and indirect input through seeds, machinery, fertilizers and pesticides. In this respect, mechanisation and intensity of production play important roles in energy consumption (Hernanz et al., 1995).

The effects of tillage systems on yield depend mainly on climate and soil conditions. A global meta-analysis by Pittelkow et al. (2015) using 5463 paired yield observations from 610 studies comparing no-tillage with conventional tillage practices across 48 crops and 63 countries showed that no-tillage reduces yields in comparison to conventional tillage systems in humid climates. However, in dry climate regions, yields of no-tillage can be equivalent or greater compared to conventional tillage systems. This suggests that no-tillage may become an important strategy for adaptation to climate-change in drier regions of the world. Growing winter wheat after winter wheat caused yield losses in treatments with reduced tillage intensity, especially with direct drilling (Arvidsson, 2010). In a long-term experiment in Tänikon (Switzerland), yields of winter wheat and rapeseed (*Brassica napus*) were similar to ploughless tillage systems when compared to yields

obtained after ploughing (Anken et al., 2004). Neugschwandtner et al. (2015) showed that in eastern Austria winter wheat yields were higher with ploughing than with no-tillage in years with a high amount of rainfall but did not differ between tillage treatments in dry years.

Detailed information on energy consumption and efficiency of different soil tillage systems for developing energy-efficient farming systems with reduced impact on climate change is missing for the Pannonian Basin.

A long-term field experiment was established in 1996 to determine the overall sustainability of four tillage systems in a Pannonian climate region with semi-arid climate conditions. The overall objective was to find the tillage system with the highest energy efficiency. In particular, this study aimed to present and discuss the yield of winter wheat and the parameters energy output, energy input, net-energy output, energy intensity and energy output/input ratio. We hypothesized that no-tillage (NT) has the lowest energy input and the highest energy efficiency. The results of the long-term experiment are relevant for several countries of the Pannonian region (Eastern part of Austria, Hungary, parts of Slovakia, the Czech Republic, Romania, Serbia, Croatia and the Ukraine).

2. Materials and methods

2.1. Experimental site and climatic conditions

The experiment was established in 1996 at the Experimental Station of the University of Natural Resources and Life Sciences, Vienna (BOKU) in Raasdorf ($48^{\circ}14'N$, $16^{\circ}33'E$; 153 m a.s.l.). The field site is located in the east of Vienna (Austria) on the edge of the Marchfeld plain, which is an important crop production region in the north-western part of the Pannonian Basin. The silt loam soil ($\text{pH}_{\text{CaCl}_2}$: 7.6 and soil organic carbon: 23 g kg^{-1}) is classified as a Calcaric Chernozem of alluvial origin (WRB, 2006). The Pannonian climate area is characterized by hot summers with low rainfall and cold winters with little snow. The mean annual temperature is 10.6°C and the mean annual precipitation is 538 mm (1980–2009). Long-term precipitation patterns show that most rainfall occurs from May to September with monthly values above 55 mm and the highest amount in June (72 mm). Long-term average temperature and precipitation during the vegetation period of winter wheat (from October until June) were 7.7°C and 362 mm (1980–2009). Mean temperatures and total precipitation during the vegetation period of winter wheat and in the whole year are shown in Table 1.

Table 1
Pre-crops of winter wheat in rotations A and B, mean temperature and mean precipitation.

	Pre-crop	Temperature ($^{\circ}\text{C}$)		Precipitation (mm)	
		Growing Season*	January–December	Growing Season*	January–December
1998	A: Sugar beet B: Maize	8.6	10.0	264	605
2000	A: Sunflower B: Oil seed rape	8.7	12.1	300	560
2002	A: Sugar beet B: Soybean	8.8	11.0	350	738
2004	A: Maize B: Oil seed rape	7.5	10.1	455	484
2006	B: Maize	6.9	10.4	373	460
2007	A: Spring durum	10.6	11.4	314	687
2008	B: Maize	8.5	11.1	478	599
2009	A: Maize	8.6	10.8	415	535
2010	B: Maize	7.8	9.6	407	717
2011	A: Sugar beet	7.9	10.5	274	385
2012	A: Winter wheat	8.6	10.9	221	415
2015	A: Sugar beet	8.7	11.6	220	384
Mean		8.4	10.8	339	547

Period between October* of previous year (seeding time) to June (harvest time).

Table 2
Tillage systems with implements used and working depths (in brackets).

Tillage operation	Mouldboard plough (MP)	Deep Conservation tillage (CT _d)	Shallow conservation tillage (CT _s)	No-Tillage (NT)
Stubble cultivation	Wing sweep cultivator (5–8 cm)	Wing sweep cultivator (5–8 cm)	Wing sweep cultivator (5–8 cm)	–
Primary tillage	Mouldboard plough (25–30 cm)	Wing sweep cultivator (16–20 cm) Subsoiler (35 cm)	Wing sweep cultivator (8–10 cm)	–
Seeding	Pneumatic universal seed drill ¹ (3 cm)	Pneumatic universal seed drill ¹ (3 cm)	Pneumatic universal seed drill ¹ (3 cm)	Pneumatic universal seed drill ² (3 cm)

¹with short disc harrow, ² without short disc harrow.

Table 3
Definition of energy efficiency parameters (according Hülsbergen et al., 2001).

	Definition	Unit
Direct energy input (E _d)	Input of diesel fuel and lubricant oil	GJ ha ⁻¹
Indirect energy input (E _i)	Seed ¹ + mineral fertilizer + pesticides + machines	GJ ha ⁻¹
Energy input (E)	E = E _d + E _i	GJ ha ⁻¹
Energy output (EO)	Energy in the harvested grain and straw – energy in the seed	GJ ha ⁻¹
Net-energy output (NEO)	NEO = EO – E	GJ ha ⁻¹
Energy intensity (EI)	EI = E/grain yield	MJ kg ⁻¹
Output/input ratio (OI)	OI = EO/E	GJ GJ ⁻¹

¹Energy input for processing, storage and sale of seed.

2.2. Experimental design and management

The experiment was conducted in a split-plot design with four replications with the purpose to perform a long-term comparison of four different tillage systems: Soil tillage – Mouldboard plough (MP), deep conservation tillage (CT_d), shallow conservation tillage (CT_s) and no-tillage (NT) – was assigned to the main plot. The plot size (24 x 40 m) for the tillage systems allowed operation with regular farm machinery. Two flexible crop rotations (A and B) were performed on sub-plots (12 x 40 m) with sugar beet or maize as central crops in the rotations A or B, respectively (cf. Neugschwandtner et al., 2015). In the period between 1997 and 2016, rotation A had a share of 50% winter wheat and rotation B 45%. The pre-crops of winter wheat in both crop rotations are presented in Table 1.

The sequence of tillage operations is shown in Table 2. The technical working width of the four furrow reversible mouldboard plough (weight: 1210 kg) was 1.7 m and for all other implements (wing sweep cultivator, subsoiler, pneumatic universal seed drill) 3.0 m. The wing sweep cultivator (weight: 1130 kg) had seven tines on two bars with a tine distance of 84 cm and a line distance of 42 cm. Behind the tine bars were mounted three rotary hoes for crumbling and a wedge ring roller for crumbling and depth adjustment. The subsoiler (weight: 773 kg) had four fixed tines (tine distance: 75 cm) with wings (34 cm width) at the bottom and a roller harrow for depth adjustment. The pneumatic universal seed drill (weight: 4550 kg) consisted of the pre-implement short disc harrow, which can be lifted up for seeding in NT. The combined chassis and packer unit after the short disc harrow is used for re-compacting the soil before seeding with 24 double disc coulters in offset. Several times the working depths were measured for a fixed implement adjustment with an air level and measuring stick after removing the loosened soil.

The yearly input rates of seeds, fertiliser and pesticides were constant during the period 1998–2015. In all treatments, sowing with a rate of 160 kg ha⁻¹ was performed and the fertilizer calcium ammonium nitrate (130 kg N ha⁻¹, 27% N) was applied in two splits. Plants were sprayed against weeds in one pass-over (with Mecoprop-P, 700 g active ingredient ha⁻¹; 2,4-D, 320 g active ingredient ha⁻¹; Carfentrazon-ethyl, 50 g active ingredient ha⁻¹) in mid-April in all plots. In the NT treatment, the non-selective herbicide Glyphosate (1575 g active ingredient ha⁻¹) was additionally applied in August before sowing.

Harvest was performed by a plot combine (1.5 m cutting width, Wintersteiger[™], Austria) with a harvest data collection system (Classic GrainGage[™], USA) in July (between 5th and 26th).

2.3. Diesel fuel consumption

For measuring fuel consumption in tillage and seeding processes, a high-performance flow-meter (PLU 116 H; AVL[®]) with a proportional-integral controller was fit into the fuel system of a four-wheel-drive tractor (power: 92 kW, weight: 6220 kg, Steyr 9125, St. Valentin, Austria). The diesel fuel consumption measurements for ploughing, cultivation (deep, shallow) and subsoiling were conducted on October 28th, 2005. Due to very low rainfall (4 mm) in October 2005, the soil was dry during tillage and seeding. The diesel fuel consumption measurement for stubble processing was done on August 11th, 2006 and for seeding on July 4th, 2012. The soil was dry during these operations. The average gravimetric soil water content (0–20 cm) was about 15%.

For the calculation of the direct energy input parameter, which is determined by fuel and lubricant oil consumption (see Table 3), measured diesel fuel consumption data for tillage (cf. Szalay et al., 2015) and seeding (cf. Moitzi et al., 2013a) were considered constant for the twelve cropping years (see Table 1). This approach is justified by the fact that the tillage processes in the twelve cropping years were done with the same machinery (tractor and implement) at the same working depth (see Table 2) and always in dry soil conditions. McLaughlin et al. (2008) has shown for fuel consumption of primary tillage implements that differences were considerably high between implements whereas differences between years were low. Constant data sets for direct energy input parameters were also used in other energy efficiency studies (cf. Hülsbergen et al., 2001; Deike et al., 2008; Lin et al., 2017).

Data for diesel fuel consumption of the pesticide sprayer (2 L ha⁻¹ for one process, weight: 925 kg), the fertilizer spreader (1.5 L ha⁻¹ for one process, weight: 300 kg) and the combine harvester (22 L ha⁻¹ for one process, cutter width: 4.5 m, weight: 10,000 kg) were obtained from the Austrian Association for Agricultural Engineering and Landscape Development (ÖKL, 2016). For the transportation of harvested winter wheat, diesel fuel consumption was calculated with the specific diesel fuel consumption coefficient of 0.09 L diesel fuel per ton of wheat and kilometer according to ÖKL (2016). A distance of five kilometers for transportation of the harvested winter wheat with tractor

and trailer was assumed. Lubrication oil consumption was set at 2% of fuel consumption (KTBL, 1994).

2.4. Energy efficiency parameters and energy equivalents

Energy efficiency parameters (Table 3) were calculated according to Hülsbergen et al. (2001). They calculated energy output including both harvested grain and straw. In the present paper, the energetic value of straw was not considered because the straw was chopped during harvesting and spread uniformly on the field. Energy in the wheat grain was set to 18.6 MJ kg⁻¹ dry matter (Hülsbergen et al., 2001), which was similar to the gross energy content in feed wheat according to the DLG (1997).

A calculation for the energy equivalent of embedded energy in farm machinery was presented by Biedermann (2009) for winter wheat production in different tillage systems for 100 ha arable area under Austrian conditions. The mass of machinery was converted into cumulative energy demand according VDI-Richtlinie 4600 (1997) using energy-coefficients from Scholz (1997). It was then divided by the estimated technical and economic life (10,000 h for the tractor, 3000 h for the combine harvester, 2000–3000 ha for the implements), to allow calculation of hourly and area-specific energy demand. The amount of the production facilities used were multiplied by the energy equivalents (Table 4).

2.5. Statistical analysis

All analyses were conducted using IBM® SPSS® Statistics 21. The requirements for analysis of variance (ANOVA) were tested with the Levene test for homogeneity of variances and Shapiro-Wilk test for normal distribution of residuals. ANOVA tests were carried out for grain yield, energy output, net-energy output, energy intensity, energy-output/energy-input-ratio to detect year and tillage effects. Overall tillage effect was tested with repeated measures ANOVA, with year as a within-subject factor and tillage as a between-subject factor. Multiple comparisons to separate means were carried out with the Student-Newman-Keuls procedure ($p < 0.05$).

3. Results

3.1. Total fuel consumption

The area-based diesel fuel consumption for producing winter-wheat was at a similar level of about 60 L ha⁻¹ for both MP and CT_d (Table 5),

while CT_s consumed a total of 48.5 L ha⁻¹ and NT a total of 36.0 L ha⁻¹. The lowest amount of diesel fuel for seeding was required for NT, where the pneumatic universal seed drill was used without the pre-implement short disc harrow.

3.2. Total energy input

The calculated total energy input ranged between 8.9 GJ ha⁻¹ and 9.4 GJ ha⁻¹ (Table 6). CT_s and NT had a lower total energy input than MP and CT_d by 4.8%. The ratio of direct energy to indirect energy (in %) was: MP 26:74, CT_d 27:73, CT_s 22:78, NT 17:83. Fertilizer energy was the highest portion of the total energy input and ranged between 42% (MP) and 44% (NT). Diesel fuel and lubricant consumption for tillage, seeding, spraying, spreading, harvest and transport was the second highest energy consumer. The share of diesel fuel and lubricant to total energy input was: MP 26%, CT_d 27%, CT_s 22%, NT 17%. The relative energy input allocated to the machinery was 19% for MP and CT_d, 20% for CT_s and 18% for NT. About 10% of the total energy input was allocated to seeds. Herbicides had the lowest energy input share with about 3% in MP, CT_d and CT_s, while NT required 11% of the total energy input for herbicides.

3.3. Grain yield and energy output

Grain yield and energy output ranged widely between years from 2243 kg ha⁻¹ and 33.3 GJ ha⁻¹ (in 2012) to 6486 kg ha⁻¹ and 101.2 GJ ha⁻¹ (in 2004) (Table 7). Grain yields and energy outputs were influenced significantly by year. Over all twelve years, mean yields and mean energy outputs did not significantly differ among tillage systems. On average across twelve years, grain yield was for CT_d 228 kg ha⁻¹ (= +5.5%), for CT_s 198 kg ha⁻¹ (= +4.8%) higher and for NT 56 kg ha⁻¹ (= -1.4%) lower than for MP (not significant).

Looking at individual years, comparison of tillage effects shows for 2004 and 2006 that NT had significantly lower grain yields than MP, CT_d and CT_s. Grain yield in 1998 was highest for NT and lowest for MP. There were no significant differences in the other nine observed years.

The calculated energy output followed the same statistical results as for grain yield.

3.4. Energy efficiency

Net-energy output ranged between 26.3 and 91.9 GJ ha⁻¹ (Table 7). In 2004, the highest net-energy output was reached in all tillage systems. The factor year influenced net-energy output significantly. Over

Table 4
Energy equivalents for production facilities.

	Unit	Energy equivalent	References
Direct energy use			
Diesel fuel	MJ L ⁻¹	39.6	Hülsbergen et al. (2001), Sørensen et al. (2014)
Lubricant oil	MJ L ⁻¹	39.0	Sørensen et al. (2014)
Indirect energy use			
Mineral fertilizer			
Calcium ammonium nitrate (27% N)	MJ N kg ⁻¹	32.2	Jenssen and Kongshaug, (2003), Arvidsson (2010)
Herbicide			
Glyphosate	MJ kg ⁻¹	454	Green (1987), CIGR (1999)
Herbicide for broadleaf weed control	MJ kg ⁻¹	259	Saling and Kölsch (2008)
Seed			
Winter wheat	MJ kg ⁻¹	5.5	Kalk et al. (1995), Hülsbergen et al. (2001)
Machinery¹⁾			
Mouldboard plough (MP)	MJ ha ⁻¹	1796	Biedermann (2009)
Conservation tillage (CT _d and CT _s)	MJ ha ⁻¹	1810	Biedermann (2009)
No-tillage (NT)	MJ ha ⁻¹	1640	Biedermann (2009)

¹⁾ Energy equivalent of the weight for tractor: 65 MJ kg⁻¹, tillage implement: 48 MJ kg⁻¹, spreader and sprayer: 55 MJ kg⁻¹, combine harvester: 70 MJ kg⁻¹.

Table 5Diesel fuel consumption (L ha^{-1}) for winter wheat in different tillage systems.

Operation	Mouldboard plough (MP)	Deep Conservation tillage (CT_d)	Shallow conservation tillage (CT_s)	No-Tillage (NT)
Stubble cultivation ¹⁾	5.7	5.7	5.7	–
Ploughing ¹⁾	18.8	–	–	–
Wing sweep cultivator ¹⁾	–	9.4	6.7	–
Subsoiling ¹⁾	–	9.4	–	–
Seeding ²⁾	6.6	7.3	7.3	5.3
Spreading fertilizer ³⁾	3.0	3.0	3.0	3.0
Spraying herbicide ³⁾	2.0	2.0	2.0	4.0
Harvesting ³⁾	22.0	22.0	22.0	22.0
Transport (5 km) ³⁾	1.7	1.8	1.8	1.7
Total	59.8	60.6	48.5	36.0

¹⁾Szalay et al. (2015); ²⁾Moitzi et al. (2013a); ³⁾ÖKL (2016).**Table 6**Direct and indirect energy inputs (GJ ha^{-1}) for winter wheat in different tillage systems.

	Mouldboard plough (MP)	Deep Conservation tillage (CT_d)	Shallow Conservation tillage (CT_s)	No-Tillage (NT)
Direct energy				
Diesel fuel, lubricant	2.4	2.5	2.0	1.5
Indirect energy				
Seed	0.9	0.9	0.9	0.9
Fertilizer	3.9	3.9	3.9	3.9
Herbicide	0.3	0.3	0.3	1.0
Machinery	1.8	1.8	1.8	1.6
Total	9.3	9.4	8.9	8.9

all twelve years, no significant influence of the factor tillage system on net-energy output was observed. In years 1998, 2004 and 2006 there were significant differences among the tillage systems with highest values for NT in 1998, while in 2004 and 2006 NT yielded the lowest net-energy output.

Energy intensity ranged between 1.43 MJ kg^{-1} and 5.25 MJ kg^{-1} dry grain (Table 7). A tillage effect was found in years 1998 and 2012. In these years, NT had the lowest energy intensity with 2.28 MJ kg^{-1} and 2.99 MJ kg^{-1} dry grain. Over all twelve years, MP and NT reached the same mean energy intensity around 2.45 MJ kg^{-1} dry grain. The mean energy intensity for CT_d and CT_s was lower than for MP by 6.1% and 10.2%, respectively (not significant).

The energy output/input-ratio ranged between 3.78 and 10.96 (Table 7). Besides the factor year, also tillage systems influenced this efficiency parameter across years. The highest energy output/input-ratios were measured in 2004 around 10.4. In 1998 and in 2012, NT had a significantly higher energy output/input-ratio than MP, whereas it was the other way around in 2006. Overall, the energy output/input-ratio was highest for CT_s and lowest for MP (with CT_d and NT showing intermediate values).

The overall ranges caused by the year were much higher than those caused by the tillage system: for net energy output 53.4 GJ ha^{-1} vs 3.6 GJ ha^{-1} , for energy intensity: 201 MJ kg^{-1} vs 0.28 MJ kg^{-1} , and for energy output/input ratio: 5.86 vs 0.71.

4. Discussion

4.1. Total fuel consumption

The choice of implements in the tillage systems determined the area based diesel fuel consumption (Moitzi et al., 2013b). Mouldboard ploughing is still a widely used tillage method in Europe under difficult conditions (heavy soils in humid regions). Arvidsson (2010) measured

diesel fuel consumption for ploughing to 20 cm depth at around 15 L ha^{-1} on a silt loam and around 30 L ha^{-1} on a clay soil. With a decrease of the ploughing depth, diesel fuel consumption can also be reduced (Arvidsson, 2010; Moitzi et al., 2014).

Comparing MP and CT_d , substitution of the plough through a subsoiler (9.4 L ha^{-1}) and a wing sweep cultivator in CT_d could not reduce diesel fuel consumption. MP and CT_d had the same area based diesel fuel consumption but showed visible effects in their plant residues incorporation. While ploughing created a soil surface without plant residues, CT_d with wing sweep cultivator and subsoiler left plant residues on the soil surface, which provide ecological services for ensuring agricultural sustainability (e.g. mitigation of soil erosion).

Seedbed preparation after ploughing can be done with power or tine harrow or combined with the seeding process (e.g. power harrow-seed drill combination or short disc cultivator-seed drill combination). Szalay et al. (2015) measured diesel fuel consumption of 8.6 L ha^{-1} for seedbed preparation with power harrow and 6.3 L ha^{-1} for seeding with a mechanical seed drill at the same experimental site. Combined seedbed preparation and seeding with a pneumatic universal seed drill required 6.6 L ha^{-1} (cf. Table 5) which was lower in comparison to a combined powerharrow-seed drill (7.6 L ha^{-1} , Moitzi, 2006 unpublished).

Shallow cultivation with a wing sweep cultivator in the CT_s treatment reduced total diesel fuel consumption by 11.3 L ha^{-1} (19%) to 48.5 L ha^{-1} . The lowest total diesel fuel consumption was measured in NT with 36.0 L ha^{-1} , which is 40% lower than with MP.

4.2. Total energy input

Total energy input in all tillage systems was below 10 GJ ha^{-1} and thereby representative of low-input systems (Lin et al., 2017). The high share of energy input through fertilization (MP – 42%, NT – 44%) in this study is characteristic of conventional cropping systems (Sartori et al., 2005; Moitzi et al., 2015).

Total energy input for CT_s and NT was lower by 4.8% in comparison to MP and CT_d . Several other studies (Hülsbergen et al., 2001; Tabatabaefar et al., 2009; Sørensen et al., 2014; Taner et al., 2016) reported a higher total energy input than we did. This difference is explained by our lower fertilizer input rates and also the non-consideration of the human labor input. In twelve different tillage scenarios analysed by Sørensen et al. (2014), the total energy input ranged between 10.5 GJ ha^{-1} (zero tillage system) and 12.7 GJ ha^{-1} (conventional tillage system with plough). Similar to our total energy input, Arvidsson (2010) reported 8.7 GJ ha^{-1} for direct drilling and 10.4 GJ ha^{-1} for mouldboard ploughing on a silt loam. A small difference between energy inputs in different tillage treatments was also reported by Deike et al. (2008) on a sandy loam. The small differences in our study may be explained by the general low-input (cf. Lin et al., 2017). The lower direct input in NT is partly compensated by a higher indirect energy input due to higher pesticide use.

Table 7

Average yield and energy parameters for winter wheat in different tillage systems and years.

	1998	2000	2002	2004	2006	2007	2008	2009	2010	2011	2012	2015	Mean
Grain¹⁾ yield (kg ha⁻¹)													
MP	2991 ^{a2)}	2959	3937	6082 ^{ab}	4090 ^b	3701	4751	4852	4969	4962	2377	3752	4119
CT _d	3238 ^{ab}	3297	4378	6486 ^b	3865 ^b	3933	5122	5630	4090	5028	2795	4302	4347
CT _s	3517 ^{ab}	3283	4121	6208 ^{ab}	4284 ^b	3942	5358	4869	4190	5404	2788	3839	4317
NT	3902 ^b	3547	3765	5548 ^a	2243 ^a	3923	5179	5352	3542	4601	2980	4134	4060
Mean	3412 BC2)	3271 B	4050 DE	6081 G	3620 BCD	3875 CDE	5103 F	5176 F	4198 E	4999 F	2735 A	4006 DE	4211
Energy output (GJ ha⁻¹)													
MP	45.3 ^a	44.8	60.4	94.7 ^{ab}	62.9 ^b	56.6	73.4	75.1	76.9	76.8	35.5	57.5	63.3
CT _d	49.2 ^{ab}	50.2	67.5	101.2 ^b	59.3 ^b	60.4	79.4	87.5	62.9	77.9	42.2	66.3	67.0
CT _s	53.7 ^{ab}	50.0	63.4	96.8 ^{ab}	66.0 ^b	60.5	83.2	75.3	64.5	83.9	42.0	58.8	66.5
NT	59.9 ^b	54.2	57.7	86.2 ^a	33.3 ^a	60.2	80.3	83.1	54.1	71.0	45.1	63.6	62.4
Mean	52.0 BC	49.8 B	62.2 DE	94.7 G	55.4 BCD	59.4 CDE	79.1 F	80.2 F	64.6 E	77.4 F	42.3 A	61.5 DE	64.9
Net-energy output (GJ ha⁻¹)													
MP	36.1 ^a	35.6	51.2	85.5 ^{ab}	53.6 ^b	47.4	64.2	65.8	67.7	67.6	26.3	48.3	54.1
CT _d	40.0 ^a	40.9	58.2	91.9 ^b	50.0 ^b	51.1	70.1	78.2	53.6	68.6	32.9	57.1	57.7
CT _s	44.9 ^{ab}	41.2	54.6	87.9 ^{ab}	57.2 ^b	51.7	74.3	66.5	55.7	75.1	33.3	50.1	57.7
NT	51.0 ^b	45.4	48.8	77.3 ^a	24.5 ^a	51.4	71.4	74.2	45.3	62.2	36.3	54.8	55.1
Mean	43.0 BC	40.8 B	53.2 DE	85.6 G	46.3 BCD	50.4 CDE	70.0 F	71.2 F	55.6 E	68.4 F	32.2 A	52.6 DE	55.8
Energy intensity (MJ kg⁻¹ grain¹⁾)													
MP	3.15 ^b	3.15	2.37	1.53	2.26	2.57	2.02	1.92	1.88	1.89	3.91 ^b	2.59	2.44
CT _d	2.97 ^b	2.89	2.19	1.44	2.41	2.39	1.84	1.66	2.37	1.86	3.32 ^{ab}	2.18	2.29
CT _s	2.59 ^a	2.80	2.21	1.43	2.12	2.27	1.67	1.82	2.11	1.64	3.21 ^{ab}	2.44	2.19
NT	2.28 ^a	2.58	2.44	1.64	2.25	2.26	1.73	1.68	2.72	1.93	2.99 ^a	2.16	2.47
Mean	2.90 CD	2.95 CD	2.26 BC	1.47 A	2.26 DE	2.41 BC	1.84 AB	1.80 AB	2.12 BC	1.80 AB	3.48 E	2.40 BC	2.31
Mean energy output/input-ratio													
MP	4.91 ^a	4.86	6.54	10.21	6.81 ^b	6.13	7.94	8.11	8.31	8.30	3.85 ^a	6.27	6.85^a
CT _d	5.31 ^a	5.41	7.27	10.85	6.39 ^b	6.51	8.54	9.40	6.77	8.37	4.55 ^{ab}	7.20	7.21^{ab}
CT _s	6.11 ^{ab}	5.69	7.20	10.96	7.50 ^b	6.88	9.43	8.55	7.33	9.52	4.79 ^{ab}	6.75	7.56^b
NT	6.78 ^b	6.14	6.53	9.72	3.78 ^a	6.81	9.07	9.37	6.13	8.03	5.12 ^b	7.26	7.06^{ab}
Mean	5.78 BC	5.52 B	6.89 D	10.44 F	6.12 BCD	6.58 CD	8.74 E	8.86 E	7.14 D	8.56 E	4.58 A	6.87 D	7.17

¹⁾ 14% moisture content; ²⁾ Statistically significant differences are shown for the year effect with capital letters and for the tillage effect with small letters.

Shifting from tillage systems with plough to non-inversion tillage systems reduces direct energy input and working time (Dutzi, 2008; Brunotte and Sommer, 2009). These are reasons why conservation tillage systems are increasingly practised in semi-arid regions world wide.

4.3. Grain yield and energy output

The range of grain yield and energy output among years was 3346 kg ha⁻¹ and 52.4 GJ ha⁻¹, respectively, and thus higher than the range among tillage systems with 287 kg ha⁻¹ and 4.6 GJ ha⁻¹, respectively. Yield variability of agricultural crops in the semi-arid region of our study are mainly caused by water shortage and heat stress (Bodner et al., 2015). Environmental factors (years and climate conditions) influenced grain yield and energy efficiency (see Section 4.4) more strongly than tillage practices.

On average across all twelve years, no significant differences were observed among tillage treatments for grain yield and energy output (although differences were observed in three individual years). There was a tendency toward higher yields with CT_d and CT_s than with MP and NT. Reduced tillage systems can result in improved yields in dry regions due to better soil water conservation whereas in wetter region the yields often are impaired (Pittelkow et al., 2015). In the Pannonian region with its semi-arid climate conditions, water is the limiting factor for plant growth. With conservation tillage-systems (CT_d, CT_s, NT) there is potential to save water in the soil, which was confirmed by a study at the same location (Raasdorf) by Thaler et al. (2012). Other factors altered by tillage treatments besides water storage might affect yield; e.g. Arvidsson et al. (2009) reported on average 1–2% lower yield for

ploughless compared with mouldboard plough in the region of Uppsala, Sweden (551 mm, 5.7 °C), explaining this by poor plant establishment caused by poor incorporation of straw residues in disc-press and direct-drilled treatments (Arvidsson, 2010).

4.4. Energy efficiency

Energy input and energy output are combined in efficiency parameters (Hülsbergen et al., 2001): net-energy output, energy intensity and energy output/input-ratio. These parameters were hardly affected by energy input, since this was very small compared with the energy content in the harvested crop (energy output) as already shown by Arvidsson (2010). Net-energy output and energy intensity were not statistically different among the tillage systems. Only the energy output/input-ratio differed among tillage systems: CT_s had a higher energy output/input-ratio than MP.

Energy output is the most important parameter, which was mainly determined by yield level and to a lesser extent by tillage system. Our experiments were conducted on a silt loam soil. Arvidsson (2010) reported that tillage effects on energetic parameters were small on a silt soil whereas this may be different on a clay soil. On a clay soil he found an increase of the output/input-ratio from 7.50 to 8.60 with a reduction in tillage intensity, despite lower net-energy gain. On a silt loam soil, the output/input-ratio ranged between 10.30 and 11.00 (Arvidsson, 2010).

In our study on a silt loam, the overall output/input-ratio for tillage systems ranged between 6.85 and 7.56 while it ranged between 4.58 and 10.44 along the experiment. This indicates a stronger dependence of

energy efficiency on climate conditions than on the tillage system.

The net-energy parameter (= energy gain) is, according to Arvidsson (2010), the most relevant parameter in determining the efficiency of cropping systems in a world of increasing food and energy demand. In this consideration, all four systems showed similar results across all twelve years (with mean values ranging from 54.1 to 57.7 GJ ha⁻¹). Hülsbergen et al. (2001) used the parameters output/input-ratio and energy intensity for determining optimum input levels from an ecological point of view. In our study, NT and MP tended on average over twelve years to have the highest energy intensity in comparison to CT_d and CT_s (not significant). The mean output/input-ratio over all twelve years was significantly highest in CT_s.

5. Conclusions

In the Pannonian region, where soil water content and climate mainly determine plant growth, soil tillage systems play a crucial role in arable farming. Ploughless tillage systems (CT_s, CT_d or NT) on a silt loam soil produced similar grain yields on average across twelve years compared to mouldboard ploughing.

The tillage systems had different diesel fuel consumptions; CT_s and NT had lower total diesel fuel consumption in comparison to CT_d and MP. As direct energy input constitutes between 17% and 27% of total energy input, lower diesel fuel consumption in these tillage systems did not automatically improve energy yield and efficiency parameters. N fertilizer was the largest energy input with more than 40% of total energy input. Year effect (determined by climatic conditions) considerably affected yield and energy efficiency parameters in all tillage systems. Over twelve years, winter wheat produced in the CT_s system attained the highest net-energy and output/input-ratio with the lowest energy intensity. The CT_s system can be recommended on silt loam chernozem as an adaptation measurement to climate change in the Pannonian basin which spreads from Eastern Austria over Hungary, parts of Slovakia, the Czech Republic, Romania, Serbia, Croatia to the Ukraine. Further investigation is required to understand the tillage effect on heavy soils in the Pannonian region.

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